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Mapping soil carbon stocks in an oceanic mangrove ecosystem in Karimunjawa Islands, Indonesia

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ABSTRACT

Mangrove ecosystems store large amounts of carbon in biomass and sediments. This so called 'blue carbon' that is captured by oceanic and coastal ecosystems plays an important role in climate change mitigation strategies. However, most biomass and carbon measurements have been conducted in coastal and delta mangroves, while oceanic mangroves are still insufficiently researched. In this paper we present results from our research on the Karimunjawa archipelago in the Java Sea north of Central Java, Indonesia, where we measured soil carbon stocks (soil total organic carbon – TOC) of an oceanic mangrove ecosystem. In previous research, we had already analyzed above-ground carbon (AGC) and below-ground biomass carbon (BGBC), so that we are now able to present the total ecosystem carbon stock. We took 35 soil samples along seven transects to analyze the relationship between (a) soil TOC and distance from shoreline, (b) total ecosystem carbon stock (AGC + BGBC + soil TOC) and distance from shoreline, (c) total C of living biomass (AGC + BGBC) and distance from shoreline, as well as (d) soil TOC and living biomass. We took another nine soil samples to analyze the distribution of soil TOC in the soil profile at a greater resolution. Our results show that there is a wide range of soil carbon stocks that varies from 3.3 t C ha^{-1} to 366.7 t C ha^{-1}. On average of the 35 samples soils contribute to 45.5% of the total ecosystem carbon stock. Overall there is no correlation between the analyzed variables. However, there is a correlation between distance from the shoreline and soil carbon stock for the longest transect and a strong relationship between soil depth and soil carbon stock for all samples. Carbon stock per increment decreases with a conspicuous drop at 15 cm.

1. Introduction

Marine and coastal ecosystems, such as mangroves, seagrass beds, and salt marshes have been identified as major carbon pools (Millennium Ecosystem Assessment, 2005; Kallesøe et al., 2008; Crooks et al., 2011; Alongi, 2014; Howard et al., 2014). The blue carbon that is captured by living organisms and stored in biomass and sediments of the world's oceans and coastal ecosystems accounts for approx. 55% of the total carbon captured by living organisms (Nellemann et al., 2009); hence, marine and coastal ecosystems play a significant role in the global carbon cycle by sequestering (capturing and storing) carbon and redistributing it (Duarte et al., 2005; Bouillon et al., 2008; Alongi, 2014; Howard et al., 2014). At the same time, we have lost coastal ecosystems at an alarming rate due to the direct impact of coastal development and indirect effects of climate change and environmental degradation (Gray, 1997; Valiela and BowenCork, 2001; Dobson et al., 2006; Airoldi and Beck, 2007; Vaquer-Sunyer and Duarte, 2008; Duarte, 2009; Waycott et al., 2009; Jones et al., 2013). This in turn leads to an accelerated release of carbon into the atmosphere that had been stored in living biomass, soils, and sediments, which contributes to the total anthropogenic CO_2 emissions (Pendleton et al., 2012).

Despite their small extent, representing only 0.5% of the global coastal area (Giri et al., 2010; Alongi, 2014), mangroves are among the most productive ecosystems that store huge amounts of carbon (Alongi, 2012, 2014; Hutchison et al., 2013). Several studies have demonstrated that biomass production and carbon stocks of mangroves and other coastal ecosystems are comparable or even greater than in carbon-rich terrestrial ecosystems such as tropical and subtropical forests (Duarte, 2009; Camacho et al., 2011; Donato et al., 2012; Alongi, 2014). Moreover, mangroves provide numerous other ecosystem services such as protection against storms, waves and coastal erosion (Vermaat and Thampanya, 2006; Das and Vincent, 2009; Duarte, 2009; Hettiarachchi

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et al., 2013; Lacambra et al., 2013), habitat and breeding ground for marine and terrestrial species (Rönnbäck, 1999; Mumby et al., 2004), provision of fishery resources (Barbier, 2000; Diele et al., 2005), nutrient filtration between land and sea (Rivera-Monroy et al., 2004), and water cycling and the maintenance of water quality (Ruitenbeek, 1994). Even though many of these services directly support local livelihoods (Armitage, 2002) and should therefore be maintained, mangroves are among the ecosystems with the highest deforestation rates (Polidoro et al., 2010).

To improve the accuracy of global and regional climate models with respect to carbon stocks and fluxes and also to develop baselines for climate change mitigation initiatives such as "REDD+ (Reducing Emissions from Deforestation and Forest Degradation), a better understanding of the spatial variation in biomass production and carbon stocks of mangrove ecosystems is necessary (Hutchison et al., 2013). So far, most of the global carbon stocks maps such as those developed by Ruesch and Gibbs (2008), Saatchi et al. (2011), or Baccini et al. (2012) do not even include mangrove ecosystems, most probably due to the limited spatial extent of mangrove forests and the scarcity of ground data, as pointed out by Hutchison et al. (2013). However, ground-based studies in various mangroves ecosystems around the world have demonstrated their high productivity in above-ground biomass (AGB) (Saenger and Snedaker, 1993; Matsui, 1998; Alongi et al., 2004; Donato et al., 2011; Cohen et al., 2013; Bhomia et al., 2016), below-ground biomass (BGB) (Komiyama et al., 2008; Lovelock, 2008; Bhomia et al., 2016) and soil carbon stocks (Donato et al., 2011; Bhomia et al., 2016) as well as high rates of carbon sequestration (Mcleod et al., 2011; Alongi, 2012; Breithaupt et al., 2012). Very recently, Atwood et al. (2017) presented the first global study on soil carbon stocks and losses, with Indonesia being the country with the highest potential CO_2 emissions from soils.

Despite the generally high values of carbon storage and sequestration in mangrove soils and biomass, Hutchison et al. (2013) show considerable differences in AGB of mangroves in different geographic regions. Based on field data obtained from the literature, the authors developed a climate-based model for potential AGB and presented a global mangrove map with patterns of AGB. According to their model, Southeast Asia is the region with the highest mangrove area worldwide (49,014 km^2 = 32% of global mangrove area) and the second highest mean AGB (230.9 t ha^{-1} compared to the global average of 184.8 t ha^{-1}). This results in a total AGB of 1.13 Pg, which represents 40% of total global AGB of mangroves. With a mangrove area of 29,865 km^2 in which 0.73 Pg of the total AGB is stored, Indonesia alone accounts for 25.8% of the global mangrove AGB. However, according to a recent study by Murdiyarso et al. (2015), most of the carbon in Indonesian mangrove ecosystems is stored below the ground. The authors estimate that 78% of the carbon is stored in the soil, and only 20% in living trees, roots or biomass, and the remaining 2% in dead or downed wood. This confirms older studies by Alongi et al. (2016, 2004, 2012), where most of the carbon from mangrove ecosystems is stored in soils and below ground biomass.

Indonesia is the country with the largest extension of mangroves worldwide and at the same time one of the countries with the highest deforestation rate. This is the reason for the increasing number of publications on mangrove biomass, carbon stocks, and carbon sequestration in Indonesia that have been published in recent years. Such research includes studies on remote sensing techniques and allometric equations to map and monitor mangrove carbon stocks by Darmawan et al. (2014, 2015), Winarso et al. (2015), Alongi et al. (2016), Candra et al. (2016), Maeda et al. (2016), and Jaya et al. (2017), investigations on mangrove carbon pools for climate change mitigation and consequences of losses and degradation (Miteva et al., 2016; Murdiyarso et al., 2015; Buditama, 2016; Richard and Friess, 2016), and a recent study on mangrove carbon stocks in relation to forest age in Lamongan (East Java) by Asadi et al. (2017). However, studies on oceanic mangroves that inhabit numerous small islands of the country are still scarce. Among the few publications on oceanic mangroves that include soil C are those by Kauffman et al. (2011) and Donato et al. (2011, 2012) in Micronesia. Moreover, Wicaksono et al. (2011, 2015, 2016) provide data on oceanic mangroves in Indonesia, but only for AGC. To increase the accuracy of existing biomass and carbon stocks models and improve the baselines for climate mitigation projects, more reliable ground-based data for this type of mangrove are needed.

In our research on the Karimunjawa archipelago in the Java Sea north of Central Java, we investigated carbon stocks of an oceanic mangrove ecosystem. We chose this archipelago because of the good environmental status of its mangroves with respect to integrity, species diversity and zonation. Therefore, it can serve as a reference for intact mangrove ecosystems on small islands of Indonesia. We have already presented our research design for carbon stock mapping (Wicaksono et al., 2011) and biomass carbon stock mapping (AGC + BGBC) using multispectral remote sensing techniques (Wicaksono et al., 2016) in previous papers. In this paper, we now focus on the soil carbon stocks (total organic carbon – TOC) of the oceanic mangrove ecosystem. We chose the transect approach to consider the impacts of mangrove zonation on changing substrates and soils and thus soil carbon stocks. Our main objectives are:

1. Measuring soils carbon stocks of the topsoil (30 cm) along seven transects in an oceanic mangrove ecosystem on the two main islands of the Karimunjawa archipelago (Karimunjawa and Kemujan).
2. Identifying the correlation between (a) soil TOC and distance from shoreline, (b) total ecosystem carbon stock (AGC + BGBC + soil TOC) and distance from shoreline, (c) total C of living biomass (AGC + BGBC) and distance from shoreline, as well as (d) soil TOC and living biomass, using soil carbon stocks of the present investigation and biomass carbon stocks that were presented by Wicaksono et al. (2016). The shoreline is based on the boundary between an inland object and the ocean, *i.e.* mangrove and the optically shallow water. It derives from an interpretation of satellite imagery. The variation of sea level is not significantly affecting the shoreline since the tide is mostly less than 1 m and never inundates any part of mangrove forest.
3. Analyzing TOC of nine soil samples at a greater resolution (5-cm intervals to 30 cm) in order to determine depths distribution of the soil carbon stock.

Our data contribute to a better understanding of variations in soil carbon stocks of oceanic mangroves.

2. Karimunjawa Islands

Karimunjawa is an archipelago consisting of 27 small islands and is located in the Java Sea between Java and Kalimantan. It extends from 5°40′39″to 5°55′00″ South and 110°05′57″ to 110°31′15″ East (Fig. 1). The Karimunjawa Islands were declared a Marine National Park in 1999 by the Indonesian Ministry of Forestry (Decree of the Minister of Forestry No. 78/Kpts-II/1999). In order to better manage the Marine National Park, the existing zonation was revised based on the Decree of the Director General of Forest Protection and Nature Conservation No. 79/IV/Set-3/2005 on June 30th, 2005. According to the Decree of the Minister of Forestry No.74/Kpts-II/2001, the Karimunjawa Islands have a total area of 111,625 ha. However, most of this area consists of water bodies, while the largest islands Karimunjawa and Kemujan only account for 1285.5 and 222.2 ha, respectively.

The Karimunjawa islands are of pre-Cenozoic (formerly pre-Tertiary) origin and primarily made of quartzite and shale that was covered by basaltic lava later (´T Hoen cited in Tomascik et al., 1997). Long erosional periods led to the formation of sediments, mainly products of crystalline schists that are correlated to the Upper-Triassic flysch formation of Sundaland (Van Bemmelen, 1949). Together with the main island of Java, the Karimunjawa archipelagoes are considered

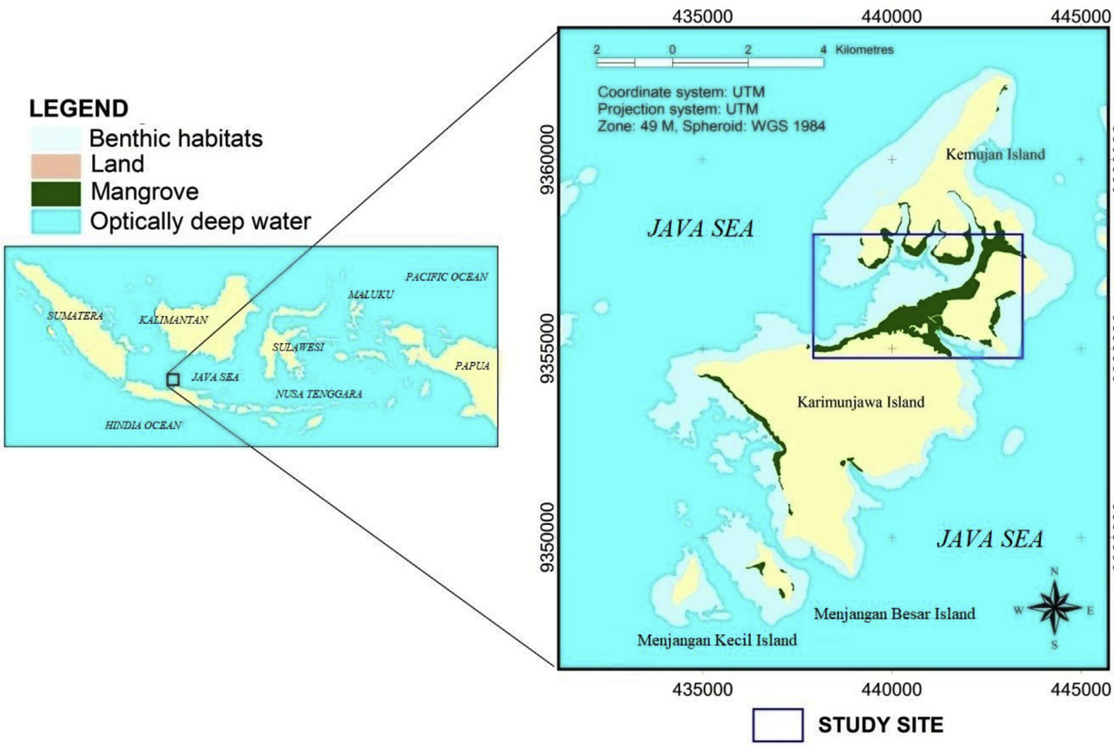

Fig. 1. Study area map.

part of the southeastern margin of Sundaland, the continental shelf that was exposed in the last glacial period (Van Bemmelen, 1949; Smyth et al., 2007). The islands can be divided into three landscape units: (a) steep hill topography dominated by sedimentary rocks from the pre-Tertiary era, that is only found on Karimunjawa Island, with Gunung Bendera as the highest point of the archipelago; (b) undulated to steep topography on pre-Tertiary sedimentary and volcanic rocks on the islands of Karimunjawa, Kemujan, Parang, and Genting; (c) flat topography dominated by alluvium and a small portion of pre-Tertiary sedimentary and volcanic rocks on all islands.

The climate of the archipelago is of the tropical monsoon type (Koeppen classification: Am) that is highly affected by Asian and Australian monsoons. According to Ongkosongo (1984), strong winds blow from the north-west and west during the west monsoonal season from November to March. They are associated with heavy rainfall of up to 40 mm day^{-1}, big waves and high humidity. During the short dry season from June to September, calmer winds blow from easterly, northeasterly, and southeasterly directions. Between the wet and dry seasons there is a transition season (*pancaroba*). The average monthly temperature is between 28° and 30 °C with only small deviation from the mean annual temperature.

According to the soil map 1:250,000 of Indonesia, dominating soil types on the islands are Dark Grey Grumusols, Grumusols, and Lithosols. Dark Grey Grumusols are well developed soils on alluvial sediments that are distributed in flat areas on all islands of the archipelago. Grumusols dominate on gentle slopes and are mainly formed from tuff and volcanic intermittent parent material. These soils are only found on the islands of Karimunjawa, Kemujan, Genting, Parang, and Nyamuk. Weakly developed Lithosols are restricted to steep hills and therefore only found on Karimunjawa Island.

Karimunjawa's marine and coastal ecosystems include coral reefs, seagrass beds and macro algae, as well as mangrove forests. Mangrove forests on the Karimunjawa archipelago are classified as oceanic mangroves (Wicaksono et al., 2011). These mangroves cover an area of about 300 ha and are mainly located on the strait between Karimunjawa and Kemujan Island. As this mangrove belt is very thick and dense, the two islands seem to be connected (Fig. 1). Mangroves are also found fringing on the shoreline in the north part of Karimunjawa Island and in the central-south part of Kemujan Island. Apart from this, small mangrove stands are found on other islands such as Cemara Kecil, Krakal Besar, Krakal Kecil, and Sintok. According to Wicaksono (2015), mangrove ecosystems on the archipelago comprise 45 species, of which 24 are true mangrove species and 21 associates.

3. Methodology

3.1. Selection of study sites and transects

Soil sample design at the landscape scale follows the variation of mangrove composition and structure from the coast to the interior. It is based on the mangrove density variation of Karimunjawa and Kemujan Islands modeled from the Normalized-Difference Vegetation Index (NDVI) (Wicaksono, 2015). We used NDVI values since they represent the abundance of vegetation (Wicaksono et al., 2016; Wicaksono, 2017). For the selection of transects, constant NDVI intervals were used. NDVI was sliced in regular intervals starting from 0.15 (starting value of vegetation cover in NDVI) to the maximum value of NDVI in the scene. We located the transects in areas with high NDVI variation, so that they cover a wide range of mangrove density and above-ground biomass. In previous research by Wicaksono et al. (2016), the zonation of NDVI values was already used as a basis for the definition of linear transects to map the biomass carbon stock. For the soil sampling here, we used the same transects as for the biomass measurements to obtain the total ecosystem carbon stock, which is the sum of AGC, BGBC and soil TOC. However, in some transect sections, slight adjustments of the routing were necessary due to limited accessibility of dense and inundated mangrove patches. The seven transects that were finally selected are located within the area of the highest variation and diversity of the mangrove forests (Fig. 2). These areas are considered as representative for a diverse and largely undisturbed oceanic mangrove in Indonesia.

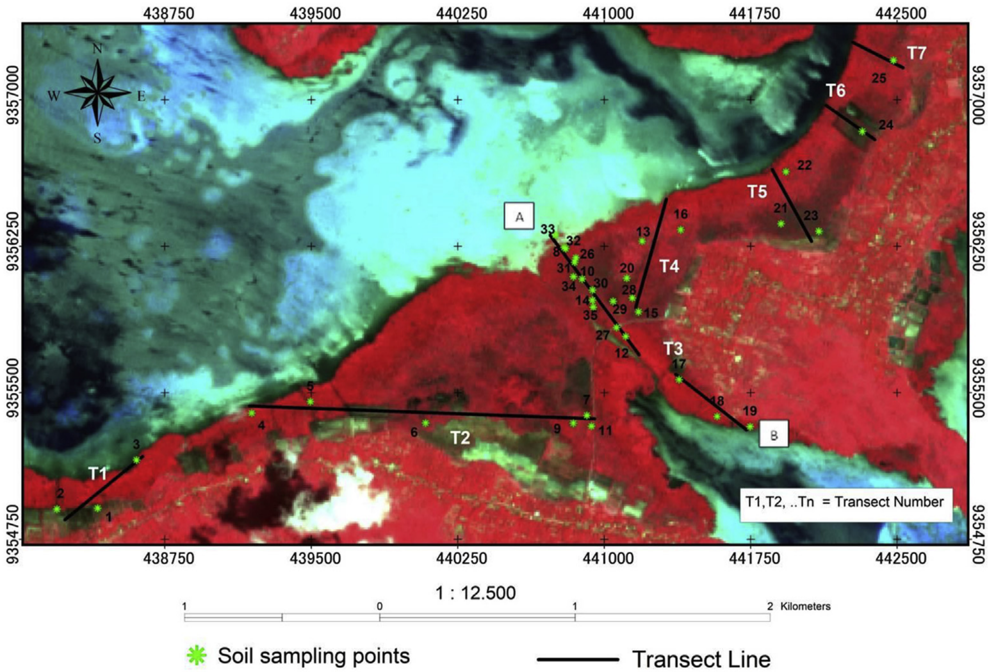

Fig. 2. Transects and soil sampling points. A is the starting point and B the end point of the longest transect (T 3).

3.2. Soil sampling and analysis

In total, 35 soil samples along the seven transects (Fig. 2) were taken using an open-face peat auger. The depth of the soil cores was 30 cm according to IPCC (2003) standard methodologies. However, when the calcium carbonate basement was reached before this depth, which was the case for four samples of transect 3 (see Table 1, numbers 29, 32, 33 and 34), the carbon stock was measured at maximum soil depth. In addition to the 0–30 cm samples, nine samples were taken in 5 cm increments to 30 cm in order to determine depths distribution of the soil carbon stock (Fig. 3). We used regular handheld GPS with accuracy between three and 7 m to plot the soil sample locations.

At each sampling site, organic litter was removed from the surface and the auger was inserted vertically into the soil. After reaching the required depth, the auger was carefully excavated and cleaned, and the undisturbed sample was collected in a numbered container. This procedure was repeated for all 35 soil samples. For the nine 5 cm increments separate samples were taken (Fig. 3), whereby the extracted soil core was cut into 5 cm segments.

The samples were analyzed in the soil laboratory of the Institute for Agricultural Technology in Yogyakarta for TOC and bulk density (BD) using Standard Operating Procedures (SOP). As recommended by Kauffman and Donato (2012), the undisturbed sediment samples were dried at 60 °C for 48 h and then analyzed for BD, which is the total dry mass divided by the sampled volume. In the case of BD, g cm^{-3} was converted into t m^{-3}. The TOC measurements were performed on 25-g-samples of dried, sieved (0.2 mm), and homogenized soil using the UV–Visible spectrophotometric method (see Wörfel et al., 1990). The UV–Visible Spectrophotometer Thermo Scientific GENESYS 20 at Universitas Gadjah Mada was used for this purpose.

We used simple correlation analyses to examine relationships between different C stocks and distance from shoreline. The different C stocks included soil TOC, vegetation carbon stocks (AGC + BGC), and total ecosystem carbon stock (AGC + BGBC + soil TOC). We also examined relationships between soil TOC and living biomass. AGC and BGBC were obtained from our previous studies (Wicaksono et al., 2011, 2016). Pearson product-moment correlation coefficients (r) with confidence levels (CL) of 95% were used to determine the relationship among the variables.

4. Results and discussion

4.1. Soil TOC analysis over all transects

The results of the soil analysis of the 35 samples (0–30 cm) from the seven transects are shown in Table 1. The soil carbon stock shows a great variation with a maximum of 366.7 t C ha^{-1} in sample 25 and a minimum of 3.3 t C ha^{-1} in sample 33. The low soil carbon stock of the latter can be explained with its location at the outer edge of the mangrove forest on the basement carbonate rock with a soil depth of only 5 cm. The AGC and BGBC values and the resulting total carbon of the living biomass are adopted from Wicaksono et al. (2011, 2016) and also show a high variation with a maximum value of 467.4 t C ha^{-1} in sample 12 and a minimum of 0.0 t C ha^{-1} in samples 24 and 33, which are free of vegetation. Overall, in 21 of the 35 samples, the BGC (soil TOC + BGBC) is higher than the AGC. The total ecosystem carbon stock varies from 3.28 t C ha^{-1} in sample 33 to 659.3 t C ha^{-1} in sample 12. On the one hand, these results show the great variations in total ecosystem carbon stocks that can be explained with changing geo-ecological conditions on a small scale (in particular variation of basement rock, soil depth, and vegetation structure). On the other hand, the values also emphasize the tremendous importance of the soil carbon pool in mangrove ecosystems, as soils contribute on average of the 35 samples to 45.5% of the total ecosystem carbon stock. However, there is a wide range from only 3.5% in sample 32–100% in samples 24 and 33 (standard deviation = 25.0). These large deviations show that there is no correlation between soil TOC and total ecosystem carbon stock, as for example near the edges, carbon-rich mangroves can grow on shallow sediments (= high biomass C, but low soil TOC), whereas in the mangroves' interior soils are often more deeply developed and accumulate organic material so that the soil TOC is frequently higher than the biomass carbon.

For Indonesian mangroves, Murdiyarso et al. (2015) provide an average total ecosystem carbon stock of 1083 ± 378 t C ha^{-1}. Moreover they report that by far most of the carbon of Indonesian mangrove ecosystems is stored in soils. For the oceanic mangroves of Karimunjawa, we come to an average of only 376.73 t C ha^{-1} for the total ecosystem carbon stock and 45.5% share of soil TOC. We assume that our considerably lower total ecosystem carbon stocks can be explained

Table 1
Analysis of 35 soil samples along seven transects (numbers correspond to Fig. 2).

No.	Core depth (cm)	d (m)	C-org (%)	BD (t m^{-3})	Soil TOC (t C ha^{-1})	AGC[a] (t C ha^{-1})	BGBC[a] (t C ha^{-1})	Total C of living biomass[a](t C ha^{-1})	BGC (t C ha[-a]	Total ecosystem carbon stock (t C ha^{-1})	% soil TOC of Total ecosystem C
1	30	183	12.75	0.584	223.40	58.00	12.77	70.77	236.17	294.17	75.9
2	30	169	19.16	0.473	272.37	140.00	36.02	176.02	308.39	448.39	60.7
3	30	41	9.96	0.672	200.86	240.00	54.82	294.82	255.68	495.67	40.5
4	30	60	13.52	0.539	219.02	320.51	76.81	397.33	295.83	616.34	35.5
5	30	97	20.24	0.441	267.65	184.17	41.74	225.91	309.39	493.57	54.2
6	30	522	6.85	0.826	169.85	57.28	17.92	75.21	187.77	245.05	69.3
7	30	206	21.26	0.441	281.14	201.64	50.02	251.66	331.16	532.81	52.8
8	30	23	0.60	1.377	24.80	242.84	63.72	306.56	88.52	331.36	7.5
9	30	311	6.92	0.782	162.43	120.40	30.25	150.65	192.68	313.08	51.9
10	30	232	1.51	1.090	49.42	125.81	33.95	159.76	83.37	209.18	23.6
11	30	212	3.43	0.881	90.72	251.19	63.14	314.34	153.86	405.06	22.4
12	30	384	9.84	0.650	191.93	377.60	89.77	467.37	281.70	659.31	29.1
13	30	187	2.98	1.035	92.61	287.70	74.55	362.25	167.16	454.86	20.4
14	30	339	23.92	0.407	292.59	144.71	37.68	182.39	330.27	474.98	61.6
15	30	498	12.31	0.517	191.28	94.65	26.14	120.81	217.42	312.07	61.3
16	30	182	20.69	0.429	266.76	243.90	63.44	307.44	330.20	574.21	46.5
17	30	134	8.25	0.595	147.28	297.38	68.78	366.17	216.06	513.46	28.7
18	30	57	1.09	1.113	36.40	340.10	79.99	420.10	116.39	456.49	8.0
19	30	27	1.74	1.079	56.37	283.97	66.52	350.49	122.89	406.87	13.9
20	30	320	1.41	1.090	46.15	193.35	53.58	246.94	99.73	293.09	15.7
21	30	348	5.90	0.683	120.93	31.37	11.85	43.21	132.78	164.15	73.7
22	30	100	23.79	0.429	306.73	276.99	66.74	343.74	373.47	650.47	47.2
23	30	445	13.96	0.551	230.76	36.63	14.38	51.01	245.14	281.76	81.9
24	30	261	13.64	0.573	234.49	0.00	0.00	0.00	234.49	234.49	100.0
25	30	248	29.19	0.418	366.71	226.31	55.85	282.16	422.56	648.87	56.5
26	30	92	1.19	1.079	38.55	119.82	30.39	150.21	68.94	188.77	20.4
27	30	470	7.18	0.848	180.53	283.15	61.63	344.78	242.16	525.31	34.4
28	30	435	6.31	0.805	149.34	119.72	31.40	151.12	180.74	300.46	49.7
29	25	380	4.02	0.852	80.57	20.34	6.66	27.00	87.23	107.57	74.9
30	30	304	3.45	0.914	86.94	144.70	37.68	182.38	124.62	269.32	32.3
31	30	113	5.36	0.911	143.25	119.82	30.39	150.21	173.64	293.46	48.8
32	10	33	1.05	1.019	10.70	230.95	60.18	291.13	70.88	301.83	3.5
33	05	0	0.64	1.024	3.28	0.00	0.00	0.00	3.28	3.28	100.0
34	25	183	6.51	0.868	140.48	120.40	30.25	150.65	170.73	291.13	48.3
35	30	384	7.23	0.804	166.70	182.78	45.17	227.95	211.87	394.65	42.2
Mean	–	–	–	–	158.37	174.81	43.55	218.36	201.92	376.73	45.5

UTM = Universal Transverse Mercator coordinate system; d = distance from shoreline (m); C-org = soil organic carbon (%); BD = bulk density; AGC = above-ground carbon; BGBC = below-ground biomass carbon; BGC = below-ground carbon (= BGBC + soil TOC).

[a] Data published in Wicaksono et al. (2011, 2016).

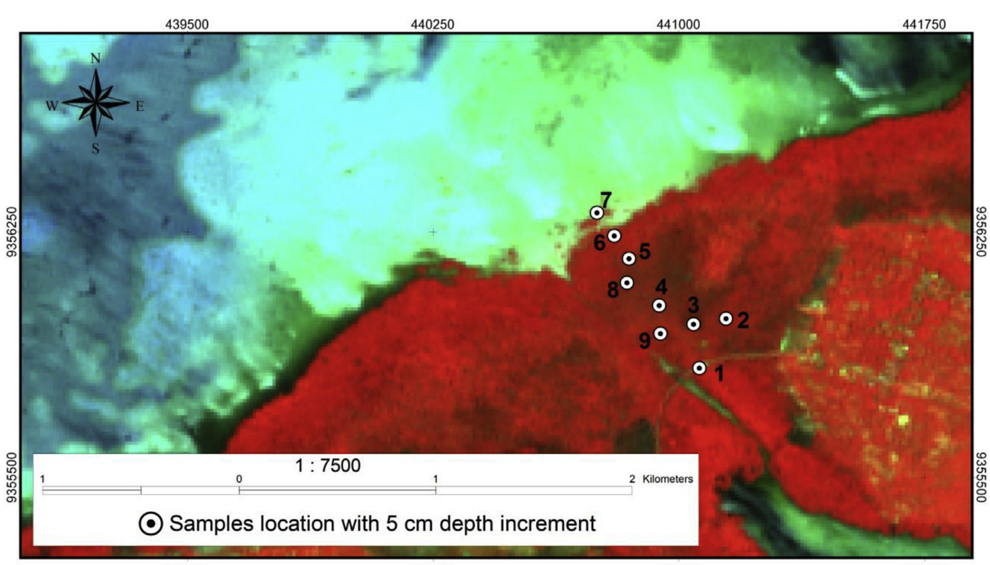

Fig. 3. Soil sample locations for the detailed mangrove TOC analysis using 5 cm vertical increments.

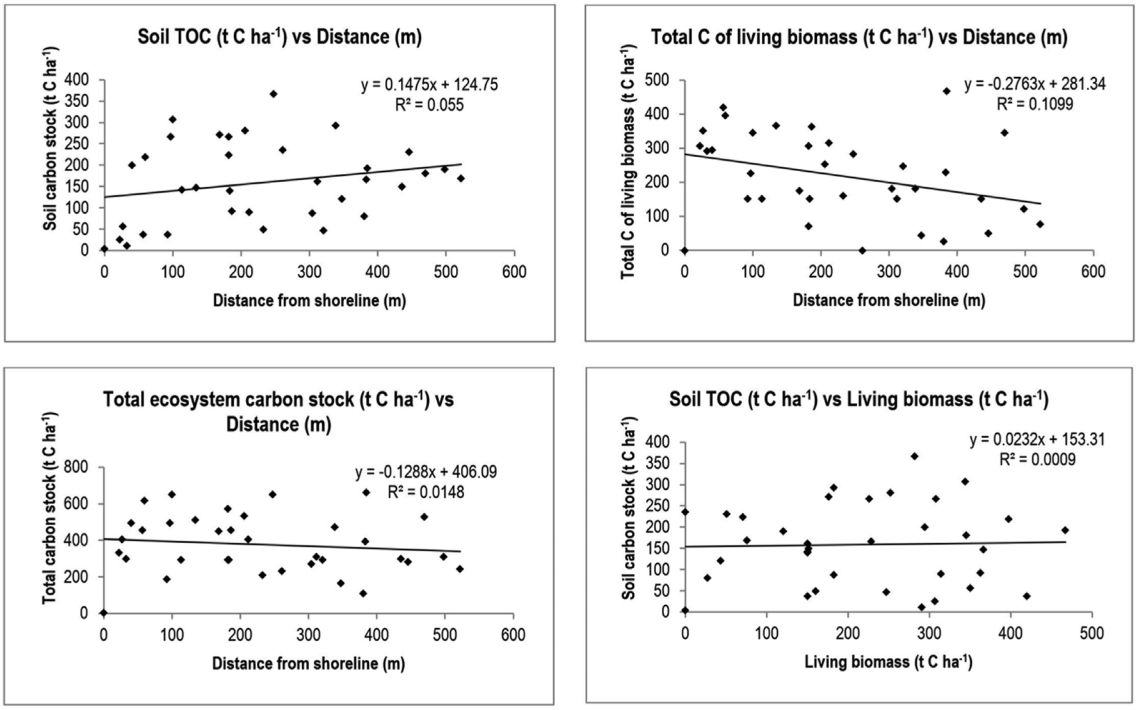

Fig. 4. (*a*) Soil TOC (t C ha^{-1}) vs Distance from shoreline (m), (*b*) Total C of living biomass (t C ha^{-1}) vs Distance from shoreline (m), (*c*) Total ecosystem carbon stock (t C ha^{-1}) vs Distance from shoreline (m), and (*d*) Soil TOC (t C ha^{-1}) vs Living biomass (t C ha^{-1}). These figures show that there is no significant correlation at 95% CL between the variables measured.

with two main factors. Firstly, Murdyarso et al. (2015) sampled up to 300 cm soil/sediment depth, while we only sampled up to 30 cm, and secondly, oceanic mangroves receive limited sediments from the islands interior compared to estuarine and riverine mangroves. Therefore soils/sediments are shallower and store less carbon. This also explains the lower share of soil TOC in total ecosystem carbon stocks. Donato et al. (2011) also come to a similar conclusion that oceanic mangroves store less soil carbon than riverine/estuarine mangroves. However, even in oceanic mangroves a large part of the total ecosystem carbon is stored in soils.

4.2. Correlation between carbon stocks and distance from shoreline

The Pearson product-moment correlation coefficients (Fig. 4a–d) show that there is no correlation between (a) soil TOC and distance from shoreline, (b) total ecosystem carbon stock and distance from shoreline, (c) total C of living biomass and distance from shoreline, and (d) soil TOC and living biomass. Possible reasons for the lack of correlation between soil TOC and distance from shoreline could be due to the inhomogeneous underlying basement rocks and sediments, as well as varying soil depths and development stages. Even though we do not have precise data on the underlying geology, we observed small-scale changes between alluvial deposits and calcium carbonate basement rock across the forest, both along the edges and in the forests' interior. Meanwhile, the above ground biomass varies due to the different composition, structure and successional stage of the mangrove forest. Another reason can be the standardized sample depth of 30 cm; if the carbon stock from the total soil depth, which increases on average from the shoreline to the inland were used, then there might be a relationship. Moreover, organic material is often trapped in root systems and sediments (accumulation) or washed away by tidal floods, respectively. This means that areas closer to the ocean would experience great wave action so that sediment could be washed away from the edge, while sediments in the interior that do not face direct wave impact should accumulate. However, Wolanski (1995) has shown that sediment deposition can be also greater at the edge, so that the accumulation in the interior can be masked. Together, this means that there is no correlation between total ecosystem carbon stock and distance from shoreline. Interestingly there is also no correlation between soil TOC and living biomass, because well-developed mangrove vegetation can be found on weakly developed soils, and vice versa, sparse pioneer mangrove vegetation is also found on deeply developed soils. Among others, we observed high biomass mangrove trees growing on shallow soils on the coral reef platform, which means high AGC, but low soil TOC. In contrast, we also found pioneer mangrove vegetation on more deeply developed soils, which means low AGC, but high soil TOC.

4.3. Detailed carbon stocks analysis for Transect 3

Transect 3 is the longest transect and has the highest variation of soils and vegetation cover. Therefore we took a closer look on this transect, which spans from the west to the east coast (Fig. 2) over a length of 1.44 km. We took 19 soil samples along this transect. Fig. 5 shows the soil carbon stocks, AGC, BGBC, total living biomass, and total ecosystem carbon stock along the transect. The x-axis displays the shortest distance from the shoreline to each sampling point. It is important to mention that this is the shortest distance to the shoreline (either to the east or west coast), and not the distance to the starting point (A) or end point (B) of the transect. This also explains why the distance decreases from 380 to 320 m and then increases again to 435 m before it again decreases towards the east coast.

The correlation analysis for sample plots along Transect 3 shows that there is a significant relationship between soil TOC and distance from shoreline (r = 0.679, R^2 = 0.461, n = 19, Sig. 95% CL), whereby the interior of the mangrove forest stores more TOC than the seaward margins. This can be explained with the protection of the interior from coastal erosion processes. An increase in soil carbon landward has also been found in other studies, such as Donato et al. (2011) and Kauffman et al. (2011). However, there is no correlation between living biomass carbon and distance to shoreline, as well as no correlation between soil TOC and biomass carbon. This can be explained by the great variations in mangrove tree composition and tree biomass; when the soil carbon

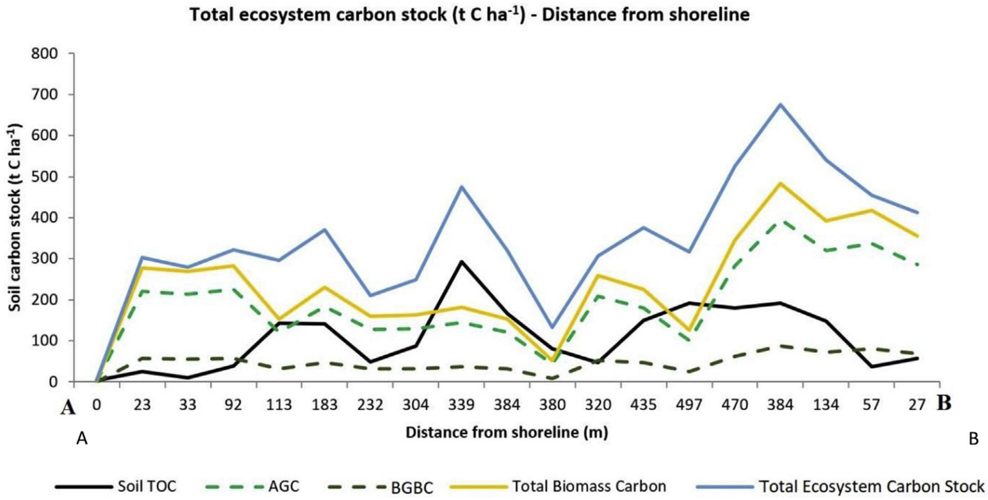

Fig. 5. Carbon stocks of transect 3 (from A to B, see Fig. 2) with representations for soil TOC, AGC, BGBC, total biomass carbon and total ecosystem carbon stock.

stock from sample plots are overlaid to the mangrove AGC map from Wicaksono et al. (2016), it is clear that even big mangrove trees can grow on shallow and carbon poor soils, and vice versa, small trees can grow on deep and carbon rich soils.

The valley point in the soil carbon curve between 232 and 320 m can be explained with shallow soils in this section; however, the low points of the biomass and soil carbon curves at 380 and 497 m are due to low mangrove density in that part of the forest (for the respective mangrove densities see Wicaksono et al., 2016). The peak of biomass carbon in the eastern part (384–27 m) can be explained with a thicker forest cover with almost homogenous tall *Rhizopora* trees.

The analysis of 5-cm increments of nine selected 0–30 cm soil samples also shows a correlation between distance from shoreline and the soil TOC ($r = 0.716$, $R^2 = 0.513$, sig. 95% CL) with the highest carbon storage in the mangrove interior and drop in the soil carbon stock between 304 and 380 m. Furthermore, most of the carbon is stored in the upper 10–15 cm of the soil, and then decreases with increasing depths (Fig. 6). Statistical analyses on all soil samples confirm that there is a strong correlation between soil depth and carbon stock ($r = -0.992$, $R^2 = 0.985$, sig. 95% CL). These results also prove that most of the carbon stock in mangrove soil is concentrated in the top layer, which is the biologically active layer that accumulates organic matter inputs from the overlying mangroves and the surrounding environment. The highest soil carbon stock was measured in sample 1 with 180.53 t C ha^{-1}, the lowest in sample 7 with only 3.28 t C ha^{-1}. These values differ considerably from measurements performed by Murdiyarso et al. (2009), who presented soil carbon stocks up to 1059 t C ha^{-1}. However, the great difference can at least be explained partly with the depths of the soil samples, as Muridyarso et al. (2009) sampled soil at depths of up to 300 cm (compare section 4.1). Consequently, their carbon estimation is much higher than in this study.

5. Conclusions

Based on the measurements of soils carbon stocks of 35 topsoil samples (30 cm) along seven transects in an oceanic mangrove ecosystem in the Karimunjawa archipelago, we derive the following conclusions:

1. Over all samples, there is no correlation between soil TOC and distance from shoreline, total ecosystem carbon stock and distance from shoreline, total C of living biomass and distance from shoreline, and soil TOC and living biomass. This is explained with inhomogeneous basement rocks, soil depths, and vegetation covers (different ages and successional stages of mangroves, different tree composition, and structural properties), as well as standardized soil

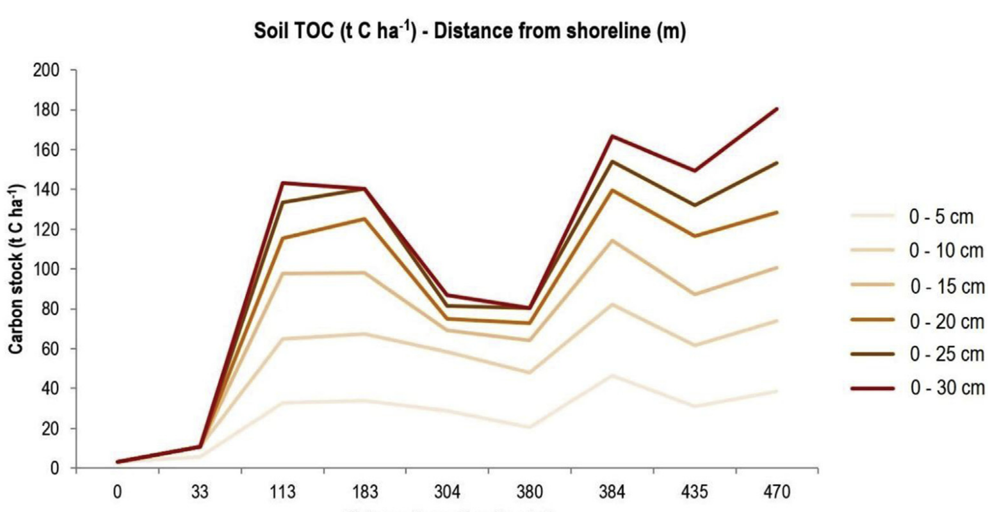

Fig. 6. Profile of accumulated soil TOC at each depth against the distance from the shoreline.

samples of 30 cm depth, which do not consider an increasing soil development with higher carbon storage towards the islands interior.

2. Over all samples, there is a strong relationship between soil depth and soil carbon stock. With increasing soil depths, the carbon stock per increment decreases with a conspicuous drop at 15 cm. In deeply developed soils, the soil carbon content often exceeds the above ground biomass carbon.
3. For the longest transect, which was studied more in detail, there is a correlation between distance from the shoreline and soil carbon stock. Here the soil carbon stock is higher with increasing distance from the shoreline. This can be explained with an on average further advanced successional stage in the mangrove interior with higher biomass production and litter fall as well as deeper developed soils that accumulate a higher amount of biomass carbon. In contrast, pioneer stands near the shoreline predominate on shallow soils that developed on the emerged coral reef platform. However, shallow soils with low carbon storage are occasionally also found further away from the shoreline in the mangrove's interior. Nonetheless, for this transect there is also no correlation between biomass carbon and soil carbon stock. As there is a correlation between distance from the shoreline and soil carbon stock only for this longest transect, but not over all transects, we suggest further studies with a higher number of long transects to prove whether and under what conditions the two variables correlate.
4. We conclude that the variation of mangrove soil carbon stock is not only determined by soil depth and distance from the shoreline, but also by other factors, which were not included in this study, such as age of the soil, the underlying basement rock or sediment, the topography, the age, composition and structure of the mangrove forest, and the variation of underground organic carbon transfer between mangrove species.

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